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# A comprehensive review on humanoid robots: perspectives from academia and industry



**Key words:** Humanoid robots; Dual-perspective analysis; Industrial applications; Technical challenges; Future directions

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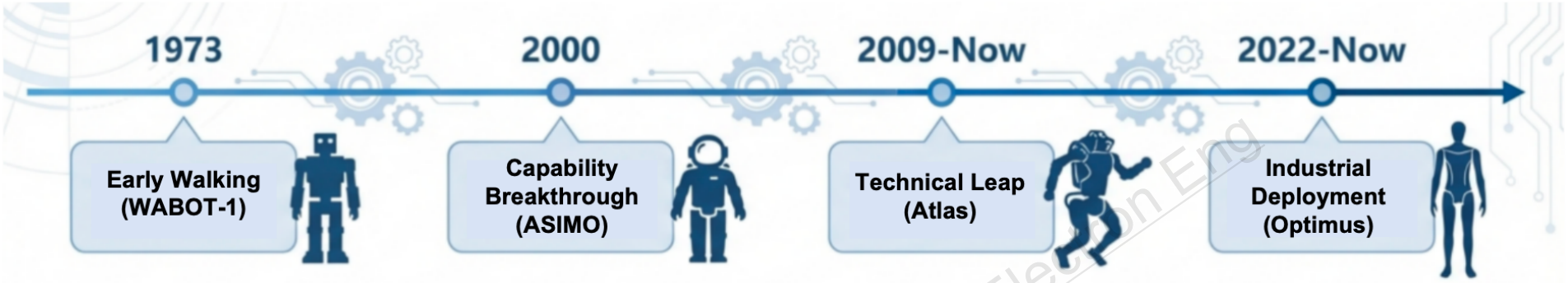
# Humanoid robots: exploding yet fragmented




## The Market Surge

**Global Investment Growth (Estimated)**


**Drivers**: Aging populations & labor shortages are transitioning robots from "Research Prototypes" to "Practical Assistants".

## The Literature Gap


### The Problem

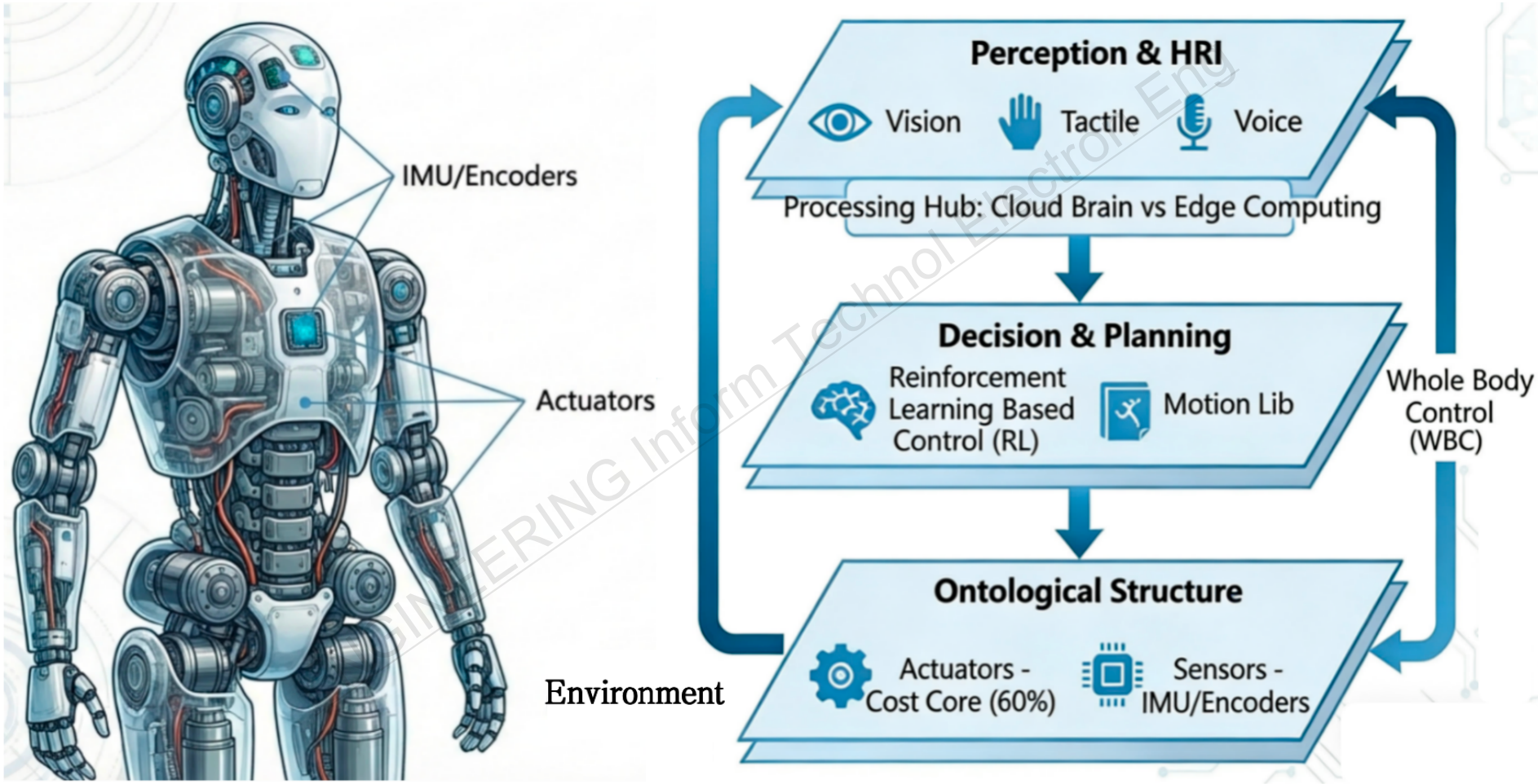
Existing reviews are fragmented and overly academic. They lack analysis of market dynamics, cost constraints, and Technology Readiness Levels (TRL).



## Our contributions

1) Comprehensive dual-perspective analysis 2) Extensive industrial product analysis
3) Systematic challenge–solution framework 4) Integrated technology assessment

# Technical architecture: a closed-loop system of perception, decision-making, and control

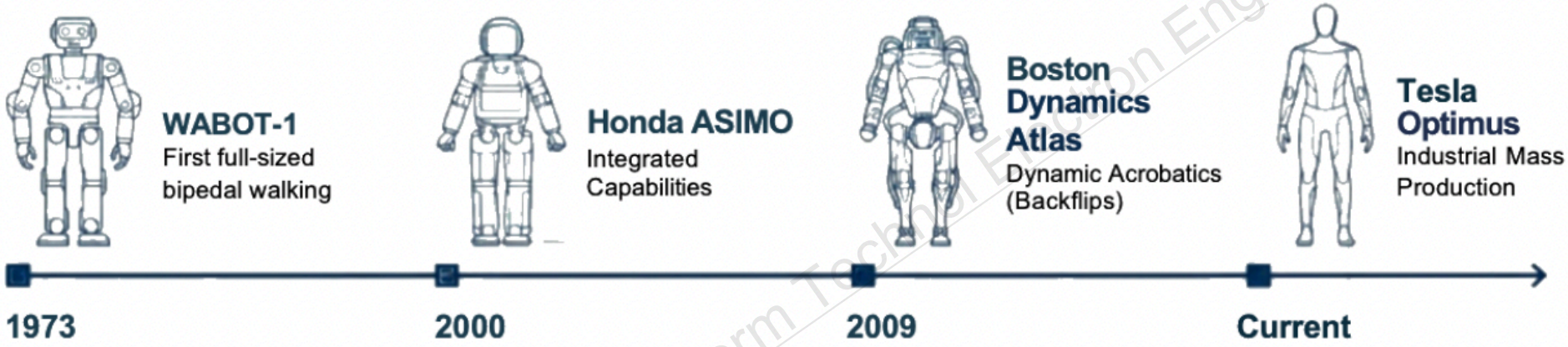



**Key technologies**

Hardware, perception & cognition, control & locomotion, and RI

# State of the art: the academic perspective

## ☐ From model-based control to learning-based adaptation






## Main trends:

- **Control shift:** transition from model-based (ZMP) to learning-based (reinforcement learning/imitation learning)
- **Open collaboration:** the "Open X-embodiment" initiative (293 authors, over 1 million trajectories solving data scarcity)
- **Efficiency:** OpenVLA (7B parameters) outperforming larger models via better data efficiency

# State of the art: the academic perspective

## ☐ Comparative analysis of market leaders

### Tesla Optimus Gen2

**Focus:** Manufacturing

**Spec:** 172cm / 56kg

**Key Tech:** Tesla Autopilot Chips, Cost <$20k target.

### Boston Dynamics Atlas

**Focus:** Dynamic Agility

**Spec:** 150cm / 89kg

**Key Tech:** Hydraulic Actuation, Heavy Payload.

### Unitree H1

**Focus:** Speed & Power

**Spec:** 180cm / 47kg

**Key Tech:** High-torque M107 Motors, 3.3 m/s speed.

### UBTECH Walker X

**Focus:** Service / Home

**Spec:** 130cm / 63kg

**Key Tech:** Safe HRI, Compliant Control.

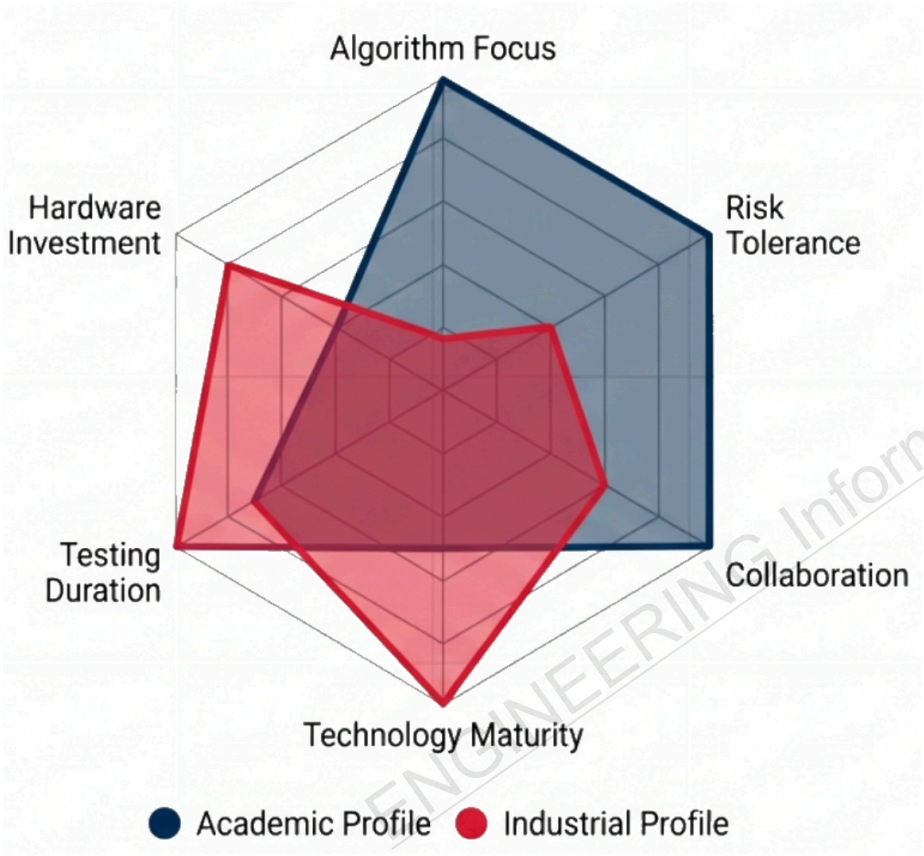
### Xiaomi CyberOne

**Focus:** Interaction

**Spec:** 177cm / 52kg

**Key Tech:** Emotion Recognition (85 cues).

# Critical insight: the academic–industrial gap




## The “Valley of Death” metrics

☐ **Technology readiness level (TRL):**

✓ Academia (TRLs 3–4: proof of concept)

✓ Industry (TRLs 8–9: qualified system)

☐ **Testing standards:**

✓ Academic prototypes (100–1000 h)

✓ Commercial requirements (MTBF>

✓ 10 000 h)

☐ **Intellectual property:**

✓ Open publication

✓ Patent protection (actuator patents dominate industry filings)

# Six major barriers to mass adoption

## 1 Hardware & Cost

Actuators are ~60% of total cost. Target: Reduce unit cost from >$150k to ~$20k.

## 2 Energy Constraints

AI GPUs (200-300W) drain standard batteries (1-2 kWh) too fast for sustained work.

## 3 Perception Limits

Trade-off between accuracy and speed. Visual/Tactile fusion is computationally expensive.

## 4 Control Complexity

Robust locomotion on uneven terrain (stairs, slopes) remains unstable under payload.

## 5 HRI Difficulties

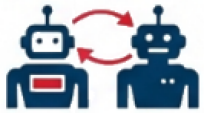
Lack of 'Social Intelligence'. Difficulty understanding sarcasm, ambiguity, and cultural context.

## 6 Ethics & Society

Job displacement risks (20-30% in manufacturing) and dual-use (weaponization) concerns.

# Promising research areas

**1. Collaborative Intelligence**



Multi-robot teams

**2. Autonomy Enhancement**

Causal Reasoning

**3. Environmental Adaptation**

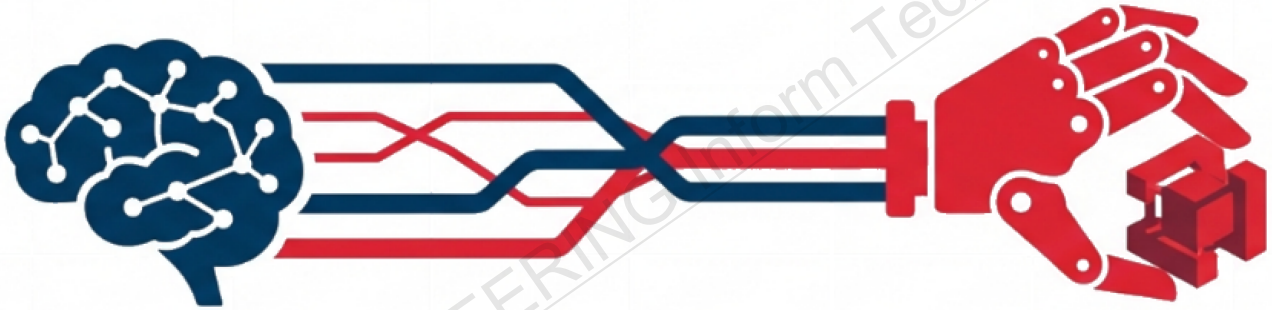
Soft robotics/Morphology

**4. HRI Optimization**

Affective computing

**5. Cross-Domain Application**

Disaster zones/Elderly care



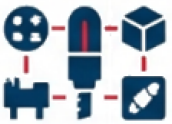
**Large Language Models**

Inter

**Embodied Action**

Inter

**6. Infrastructure**



Standardized modular components

**7. Ethical Frameworks**

Safety assurance

**Key Shift:** From **"Code-to-Walk"** to **"Language-to-Action"** end-to-end learning

# Future outlook

- This survey provides actionable guidance for advancing the field toward more capable, affordable, and socially-integrated humanoid robots.

| Term | Outlook |
| --- | --- |
| Near-term (1–3 years) | Limited commercial deployment in controlled environments with improved actuator efficiency and foundation model integration |
| Medium-term (3–5 years) | Multi-robot collaboration breakthroughs and deployment in semi-structured environments with cost reductions via standardization |
| Long-term (5–10 years) | Truly autonomous humanoid robots operating in complex, unstructured environments with large-scale deployment across diverse applications |

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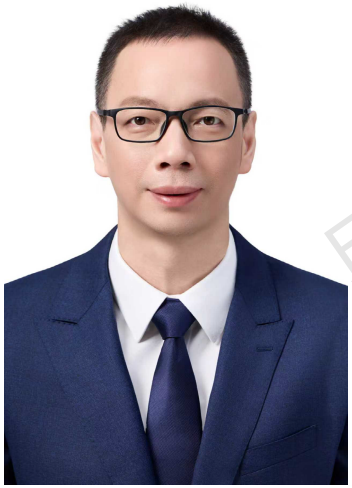

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